ÉCOLOGIE

Climate-based health monitoring systems for eco-climatic conditions associated with infectious diseases.

J. E. Pinzon (1, 2)*, J. M. Wilson (3) & C. J. Tucker (2)
(1) Science systems and applications, Inc. (SSAI)
(2) Hydrospheric and biospheric sciences laboratory, NASA Goddard space flight center, Code 614.4, Greenbelt, Maryland 2077.
(3) Georgetown University Medical Center, Imaging Science and Information Systems Center
*Correspondance : Hydrospheric and biospheric sciences laboratory, NASA Goddard Space Flight Center, Code 614.4, Greenbelt, Maryland 20771
Phone: 301-614-6685, E-Mail: Jorge.E.Pinzon.l@gsfc.nasa.gov

Manuscrit n° 2761-5. "Atelier sur les fièvres hémorragiques virales". Reçu le 30 mars 2005. Accepté le 12 juillet 2005.

Résumé : **Systèmes de surveillance de santé des maladies infectieuses, basés sur les conditions climatiques.**

Malgré un siècle de confiance et d'optimisme dans la médecine et la technologie modernes, conforté par la prévention, la lutte, souvent couronnées de succès, les maladies infectieuses demeurent un défi majeur et permanent de santé publique. Le dépistage efficace et le contrôle de ces maladies nécessitent de solides méthodes de prévision et d'initiatives capables de donner l'alerte précoce d'une épidémie. La mise en lien d'informations à l'échelle de paysage, voire encore à plus grosse échelle, à des données à l'échelle de l'activité épidémique se révèle particulièrement intéressante.
Ces dernières années, l'épidémiologie de paysage a utilisé la détection satellite et les systèmes d'information géographique qui, de l'échelle locale à l'échelle mondiale, transmettent les tendances climatiques spatiales et temporelles ; elles peuvent influencer l'intensité d'une maladie vecteur-soutenue et prévoir les risques occasionnés par l'épidémie. Nous proposons un condensé des données de base, ainsi qu'un condensé sur la recherche récente concernant la détection satellite et les applications du GIS (système d'information géographique) en santé publique.

épidémiologie de paysage
télédétection satellite
GIS
balance spatiale et temporelle permanente
dynamique éco-climatique
surveillance épidémiologique
maladie infectieuse
fièvre hémorragique Ebola
fièvre de vallée du Rift
peste
encéphalite arboviral
Afrique intertropicale

Summary:

Despite a century of confidence and optimism in modern medicine and technology inspired by their often successful prevention and control efforts, infectious diseases remain an omnipresent, conspicuous major challenge to public health. Effective detection and control of infectious diseases require predictive and proactive efficient methods that provide early warning of an epidemic activity. Of particular relevance to these efforts is linking information at the landscape and coarser scales to data at the scale of the epidemic activity. In recent years, landscape epidemiology has used satellite remote sensing and geographic information systems as the technology capable of providing, from local to global scales, spatial and temporal climatic patterns that may infuence the intensity of a vector-borne disease and predicts risk conditions associated with an epidemic. This article provides a condensed, and selective look at classical material and recent research about remote sensing and GIS (geographic information system) applications in public health.

landscape epidemiology
satellite remote sensing
GIS
continuous spatial and temporal scale
eco-climatic dynamics
epidemiological surveillance
infectious disease
Ebola hemorrhagic fever
Rift Valley fever
plague
arboviral encephalitis
Sub Saharan Africa

Introduction

Great optimism about the treatment, control and prevention of infectious diseases in the past century was a common feeling in the developed world. The establishment and discoveries of the modern bacteriology, epidemiology and therapeutics led to enormous progress, improving life span and notably decreasing disease transmission and host susceptibility. This progress shaped modern medicine and public health policies, reaching better nutrition and housing, safer food and water, and improving hygiene and sanitation. However, the developing world had not the same success with infectious diseases. As pointed out in recent scientific journals and popular press (5, 7, 9, 12, 21), while we are certainly better than we ever were in terms of treatment, control and prevention of infectious diseases, the risk of spreading them also increases by changes in society, technology, and environment (natural and human-induced). A series of outbreaks and epidemics of emerging diseases (e.g. Ebola hemorrhagic fever, hantavirus, SARS, H5N1 avian influenza), and re-emerging diseases (e.g. plague, Rift Valley fever, West Nile virus, malaria) indicate not only the impact of microbial and viral factors on public health but also the relevance of the dynamic interaction between these factors and social and environmental determinants.
In recognition of these important trends, health organizations have called for the development and implementation of new disease surveillance tools (4, 25). The new tools include the application of landscape epidemiology that should characterize climatic and environmental conditions of vector habitats and derive a spatial and temporal disease risk. A major obstacle in designing and implementing a sampling system to adequately monitor a potential epidemic is its dependence on spatial

or temporal data discontinuities. However, many of the parameters associated with environmental change and patterns of disease can be continuously sensed remotely by instruments onboard aircraft and satellites, and modeled spatially with specialized computer software. Moreover, many factors have contributed to overcome earlier reservations regarding the utility of aerospace-based technologies. Commendable among them are the significant advances in computer processing and improvements in data acquisition, and the NASA's efforts to make their technologies more readily available to the widest possible user community. NASA has created programs, like the Public Health Program Element of the NASA Applied Sciences Program, to extend products derived from science information, models, technology, and other capabilities into partners' decision support tools for public health, medical, and environmental health issues (13, 14). Thus, remote sensing and geographic information systems (GIS) technologies have been extensively used to describe local and landscape-level features that influence the patterns and prevalence of disease and then model the occurrence of the health event in space and time. This article provides a condensed, and selective look at classical material and recent research about remote sensing and GIS applications in public health.

Satellite remote sensing systems

The temporal and spatial distribution of most infectious and vector-borne diseases (pathogens, vectors, zoonotic reservoirs) and their interactions with humans are influenced by a combination of environmental factors such as vegetation, temperature, landscape structure, humidity, and rainfall (11). Most of these factors are currently measured, observed, and/or modeled with data from existing remote sensing systems (1, 10, 15, 19, 23). Satellite sensors are designed with a variety of temporal, spatial, and spectral characteristics and resolutions to provide measurements of many environmental change parameters, some for the first time. More than 90 different missions are on orbit carrying over 200 different instruments (14, 15). Specific requirements for a surveillance system should include a feasibility analysis for integrating specific observation from Earth-Sun system science missions and models as well as a description of the state-of-the-art of Earth observation technology that may be applied to the surveillance solutions. Table 1 listed relevant specific parameters and their projected source of some of the key environmental elements. The Center for Health Applications of Aerospace Related Technologies (CHAART) at the NASA Ames provides a more detailed evaluation of the satellite-sensor characteristics to better apply these technologies and capabilities (1, 15). CHAART has developed a set of web pages to evaluate sensors for health applications. These pages indicate new opportunities for exploring the connections between the landscape and health using existing and yet to be acquired remotely sensed data (15).

Since mid 1981, most studies of global or regional vegetation conditions have used data from the Advanced Very High Resolution Radiometer (AVHRR) instruments in the NOAA series of polar orbiting meteorological satellites (3, 6, 18). Data from the AVHRR instruments that has been used for epidemiological studies includes apparent surface temperature, derived from the thermal channels, and the normalized difference vegetation index (NDVI), a measure of the photosynthetic capacity of vegetation (10, 19, 24). NDVI time series data is normally used as proxy for rainfall in these studies. These data are derived from measurements made by the AVHRR instruments carried on the NOAA series of meteorological satellites. The NDVI is computed from the red (550-700 nm) and near infrared (730-1100 nm) channels of the AVHRR as NDVI = (ir-red)/(ir+red).

Improved satellite data have been available from the SPOT Vegetation instrument, a 1-km time series instrument that produces an NDVI product since 1998. NDVI and thermal data have been available from the MODIS instruments on the Terra and Aqua platforms of NASA since late 1999. A crucial and unique feature of the NDVI data is that it has been intercalibrated from the AVHRR, SPOT Vegetation, and MODIS instruments. Thus, should one or more of the NDVI-providing instruments fail, one can switch to another source of NDVI data. Furthermore, since it is intercalibrated, the AVHRR NDVI long record (back to 1981) can be used to provide environmental indications of potential epidemics and to understand the severity of an outbreak (3, 18, 19). In fact, by comparing proxy vegetation response patterns, as detected by the remotely sensed NDVI, a set of remote sensing indications reveal unusual climatic conditions associated temporally and spatially with trigger points and leading edge of infectious and vector-borne diseases such as Ebola hemorrhagic fever, Rift Valley fever, and bubonic plague epidemics (10, 19, 24).

Landscape epidemiology

Most of the research involving remote sensing data and GIS to study disease has focused on identifying and mapping vector habitats, or assessing environmental factors related to vector habitat quality (1, 10, 16, 17, 22, 23). A basic understanding of the area's landscape ecology is useful for predicting the future course of epizootics and identifying areas of high risk for humans. For example, in response to the need for more spatially and temporally complete information, CDC has partnered with NASA to explore the use of remote sensing products and models into the CDC's ArboNET/plague surveillance system (PSS) (10, 14). The incorporation of Earth science data was intended to improve the PSS's accuracy with regard to spatial and temporal dimensions of plague vector habitats. A few pilot studies are now underway in certain regions of New Mexico, Arizona, and Colorado (four corners states) to evaluate, validate and benchmark the use of datasets of the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor aboard the Earth Observing System (EOS) Terra and Aqua Satellites, LandSAT TM data, Shuttle Radar Topography Mission (SRTM), Tropical Rainfall Measuring Mission (TRMM), among other remote sensing platforms provided by NASA and NOAA. A better understanding of the area's landscape ecology has

Table I.

Specific parameters of current sensor systems for identifying and mapping key environmental elements in disease surveillance.
Paramètres spécifiques des systèmes de détection actuels pour identification et repérage des éléments environnementaux-clés dans la surveillance de la maladie.

	Earth-Sun System Science Results	Source
Atmospheric and Weather	Precipitation	TRMM
	Temperature	MODIS
	Humidity	MODIS
Vegetation	Habitat quality	AVHRR/MODIS NDVI
Land Use/ Land Cover	Land Use	MODIS/LANDSAT
Topography	Surface Topography	SRTM
Relevant Earth-Sun System Science Modeling Efforts (relevant in Public Health)	Visualization technology	RS/GIS visualization tools
	Outbreak indications and warnings	RS Disease / Eco-climatic models

been obtained combining time series analysis of the AVHRR NDVI and landcover information from Landsat TM. These results should facilitate the mathematical modeling designed to investigate the role of climatic factors in the changing frequency of human plague cases in the American Southwest.

The need to improve our ability to respond to an epidemic threat promptly and effectively, shifted the application of remote sensing and GIS to characterize and monitor spatial and temporal landscape patterns that collectively define vector and human population dynamics related to disease transmission risk (2, 8, 19). For example, PINZON *et al.* (19) explore the relationships among climate variability, and geographic disease patterns of the Ebola hemorrhagic fever to infer vector ecology and evaluate disease emergence and transmission risk.

Ebola hemorrhagic fever

Ebola hemorrhagic fever, named after the Ebola River in Central Africa, first appeared in June 1976, during an outbreak in Nzara and Maridi, Sudan. In September 1976, a separate outbreak was recognized in Yambuku, Democratic Republic of the Congo (DRC). One fatal case was identified in Tandala, DRC, in June 1977, followed by another outbreak in Nzara, Sudan, in July 1979. Ebola hemorrhagic fever outbreaks results in a very high mortality of patients who contract the disease: from 50 to 80% of infected people perish from this highly virulent disease. Death is gruesome, with those afflicted bleeding to death from massive hemorrhaging of organs and capillaries.

The disease was not identified again until the end of 1994, when three outbreaks occurred almost simultaneously in Africa. In October, an outbreak was identified in a chimpanzee community studied by primatologists in Taï, Côte-d'Ivoire, with one human infection. The following month, multiple cases were reported in northeast Gabon in the gold panning camps of Mekouka, Andock, and Minkebe. Later that same month, the putative index case of the 1995 Kikwit, DRC, outbreak was exposed through an unknown mechanism while working in a charcoal pit. In Gabon, two additional outbreaks were reported in February and July 1996, respectively, in Mayibout II, a village 40 km south of the original outbreak in the gold panning camps, and a logging camp between Ovan and Koumameyong, near Booue. The largest Ebola hemorrhagic fever epidemic occurred in Gulu District, Uganda from August 2000 to January 2001. In December 2001, Ebola reappeared in the Ogooue-Ivindo Province, Gabon with extension into Mbomo District, The Republic of the Congo lasting until July 2002.

Of interest is the seasonal context and occasional temporal clustering of Ebola hemorrhagic fever outbreaks. Near simultaneous appearances of Ebola epidemics in Nzara, Sudan and Yambuku, DRC in 1976 occurred within two months of each other in two geographic locations separated by hundreds of kilometers involving two separate viral strains (Sudan and Zaire EBO strains). The outbreaks of Taï, Côte-d'Ivoire; Mekouka, Gabon; and Kikwit, DRC in late 1994 also occurred within months of each other in three different geographic regions involving two different viral strains (Côte-d'Ivoire and Zaire EBO strains). Fifteen years passed between the 1976-1979 and 1994-1996 temporal clusters of Ebola cases without identification of additional cases.

Despite extensive field investigations to define the natural history of the Ebola hemorrhagic fever virus, the origin and mechanism of disease transmission, from reservoir to humans, remains a mystery. Nevertheless, Ebola hemorrhagic fever and several other infectious diseases, e.g. rift valley fever, cholera, hantavirus, have been studied using satellite data

Figure 1.

The time series behavior of the NDVI data from the documented outbreak sites of Ebola hemorrhagic fever. Note the outbreaks all occur toward the end of the rainy season.

Le comportement de séries chronologiques des données NDVI à partir des régions où une épidémie de fièvre hémorragique due au virus Ebola a été identifiée.
À noter : toutes les épidémies se déclarent vers la fin de la saison des pluies.

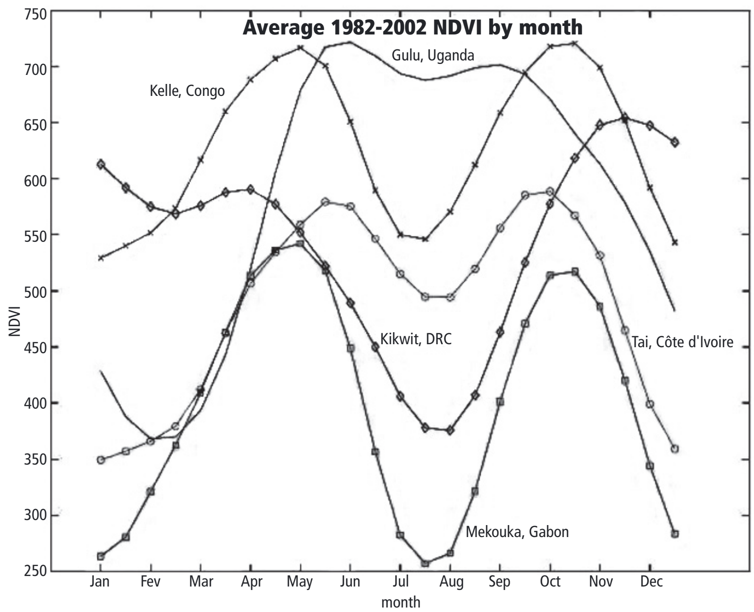
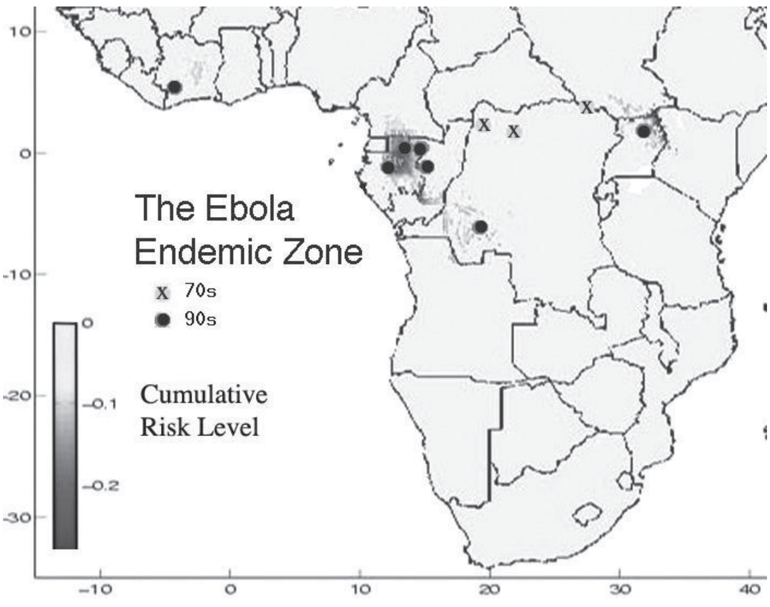


Figure 2.

Our analysis identifies areas where Ebola hemorrhagic fever is endemic. If confirmed by groundwork, this is the "Ebola Hot Zone".

Notre analyse identifie les régions où la fièvre Ebola est endémique.
Si celle-ci est confirmée par le travail de terrain, il s'agit de la « zone virulente Ebola ».



that suggest climatic modulation of incidence. The NDVI AVHRR-imagery time series is used to (1) identify proxy indicators of Ebola risk, and characterize areas endemic to this infectious disease. In this study the NDVI characterizes the vegetation type(s) associated with Ebola outbreaks and variations in the wet and dry seasons were directly associated with Ebola outbreaks. Landsat data confirmed that all Ebola hemorrhagic fever outbreaks occurred in either tropical moist forest or gallery tropical forest in a matrix of savanna (22).

The singular value decomposition analysis, a powerful mathematical tool, is used to identify the time series behavior of the NDVI data from the documented outbreak sites of Ebola hemorrhagic fever (figure 1). The method expands on the findings of PINZON *et al.* (19) that explores the relationships among climate variability, and geographic disease patterns of the Ebola hemorrhagic fever to infer vector ecology and evaluate disease emergence and transmission risk. This enabled us to restrict the analysis to only areas of tropical moist forest or gallery tropical forest in Africa. This study, integrating the spatial transmission risk of the PINZON's *et al.* results, has identified the "*Hot Zone*" of Ebola hemorrhagic fever in Africa (figure 2). This is the area where our analysis indicates Ebola hemorrhagic fever is endemic, thus directing more study to specifically these areas.

Summary and directions for future research

The use of remote sensing and GIS has many implications for infectious surveillance systems because it provides to users the ability to respond to an epidemic threat promptly and effectively. Field observations on environmental conditions, including vegetation, water, and topography, are quantified using the spatial analysis capabilities of image processing, time series and statistical analysis and GIS. These tools allow us to directly interpret remote sensing data and facilitate the characterization of the landscape in terms of vector, pathogen prevalence, and disease emergence and transmission risk, even in where field data are unavailable. This makes the Earth space-science products a powerful set of tools that supports disease surveillance systems (4, 13, 25).

However, most biosurveillance research and development focuses on anomalies in automated news alert services (e.g., BioWatch) and human clinical data (i.e., spikes in uses of International Classification of Disease diagnostic codes). The international community learns of outbreaks via ProMED media tracking and official disease reports facilitated by the World Health Organization (WHO). Both methods are prone to subject matter and geographic coverage limitations due to a country's ability to support disease surveillance and response, as well as its willingness to share that information with the international community.

New research expands upon ProMed's and uses transportation modeling to assess the potential for a bioevent to translocate from one place to another. The result should help in shaping management and response to biological catastrophic events, with broad applicability to monitoring any event that induces a disturbance in society. There thus is an opportunity to greatly enhance these efforts by incorporating satellite environmental indications and warnings (I&W)s at a variety of spatial and temporal sampling grid. A module should provide automatically environmental disease signatures at a variety of temporal and spatial resolutions and provide probabilistic predictions of potential catastrophic bioevents as a function of environmental changes together with uncertainties and estimates of error. It would enable earlier warning potential to responders to produce actionable intelligence in case of a catastrophic bioevent, and hence should be part of an integrated biosurveillance portfolio. It should also be an opportunity to enrich the value of the environmental I&Ws obtained from remote sensing data and models by combining them with the multiple data sources available in such a system. It will potentially reduce the number of false positives reported to the global community and should allow an automated priming alert system.

A recent study conducted by ROUQUET *et al.* (20) on the human Ebola virus outbreaks and monitoring of wild animal mortality, indicates that all human cases resulted from handling infected wild animal carcasses. This study showed that Ebola virus is primarily a disease of non-humans primates that is spread by an unknown vector and move across the human-wild divide through hunting and consumption of great apes, causing severe hemorrhagic fever in both human and non-human primates. The disease is then spread to families and hospital workers, creating the conditions of an epidemic. Thus, epidemiologic surveillance of animal mortality is helping to prevent and control the emergence of the disease in human populations. From this perspective, we should formulate an epizootic (animal-based disease) model for the great apes populations that ingests remote sensing data, and coupling this with standard epidemic (human disease) surveillance systems. This should enable us to identify more precisely environmental conditions and epidemic patterns and the circumstances in which the disease causes a large number of non-human and human primate cases. By identifying the environmental conditions of a potential large outbreak, the model not only should reduce human cases but also should alert wildlife conservation authorities about an imminent risk in wild animal populations weeks before the outbreak happens.

Acknowledgements

We thank the contributions made to the integration of remote sensing data by our colleagues at NASA/GSFC.

Références bibliographiques

1. BECK LR, LOBITZ BM & WOOD BL - Remote sensing and human health: New sensors and new opportunities. *Emerg Infect Dis*, 2000, **6**, 217-227.
2. BECK LR, RODRÍGUEZ MH, DISTER SW, RODRÍGUEZ AD, REJMANKOVA E *et al.* - Remote sensing as a landscape epidemiological tool to identify villages at high risk for malaria transmission. *Am J Trop Med Hyg*, 1994, **51**, 271-280.
3. BROWN ME, PINZÓN JE & TUCKER CJ - New vegetation index data set available to monitor global change. *News, EOS Transactions, AGU*, 2004, **85** (52), 565 and 569.
4. CDC - Revising CDC's guidelines for evaluating surveillance systems. In: *MMWR*, 1998, **47**, http://www.cdc.gov/ncidod/osr/index.htm.
5. COHEN ML - Changing patterns of infectious disease. *Nature*, 2000, **406**, 762-767.
6. CRACKNELL AP - *The Advanced Very High Resolution Radiometer*. Taylor & Francis, London, 1997, p. 534.
7. DI GIULIO DB & ECKBURG PB. Human monkeypox: an emerging zoonosis. *Lancet Infect Dis*, 2004, **4**, 15-25.
8. DISTER SW, FISH D, BROS S, FRANK DH & WOOD BL - Landscape characterization of peridomestic risk for Lyme disease using satellite imagery. *Am J Trop Med Hyg*, 1997, **57**, 687-692.
9. GARRET L – *The coming plague- newly emerging diseases in*

a world out of balance. Penguin books, New York, 1994, p. 750.

10. LINTHICUM KJ, ANYAMBA A, TUCKER CJ, KELLEY PK, MYERS MF & PETERS CJ - Climate and satellite indicators to forecast Rift Valley fever epidemics in Kenya. *Science*, 1999, **285**, 397-400.
11. MEADE MS, FLORIN JW & GESLER WM - *Medical Geography*. The Guilford Press, New York, 1998.
12. MORENS DM, FOLKERS GK & FAUCI AS - The challenge of emerging and re-emerging infectious diseases. *Nature*, 2004, **430**, 242-249.
13. NASA - NASA Earth science applications program. NASA Earth science Enterprise Division Plans, 2003, http://science.hq.nasa.gov/strategy/index.html.
14. NASA – NASA Earth Science Enterprise Strategy. NASA Earth Science Enterprise Division Plans, 2003, http://science.hq.nasa.gov/strategy/index.html.
15. NASA - CHAART's role in public health. Center for health applications of aerospace related technologies, 2003, http://geo.arc.nasa.gov/sge/health/chaart.html.
16. PARMENTER RR, YADAV EP, PARMENTER CA, ETTESTAD P & GAGE KL - Incidence of plague associated with increased winter-spring precipitation in New Mexico. *Am J Trop Med Hyg*, 1999, **61**, 814-821.
17. PETERSON AT, BAUER JT & MILLS JN - Ecologic and geographic distribution of *Filovirus* disease. *Emerg Infect Dis*, 2004, **10**, 40-47.
18. PINZÓN JE, BROWN ME & TUCKER CJ - Satellite time series correction of orbital drift artifacts using empirical mode decomposition. In: HUANG NE & SHEN SS (Eds) - *Hilbert-Huang Transform: Introduction and applications*. World Scientific, Singapore, 2005, pp. 193-216.
19. PINZÓN JE, WILSON JM, TUCKER CJ, ARTHUR R, JAHRLING P & FORMENTY P - Trigger Events: Enviro-Climatic Coupling of Ebola Hemorrhagic Fever Outbreaks. *Am J Trop Med Hyg*, 2004, **71**, 664-674.
20. ROUQUET P, FROMENT JM, BERMEJO M, KILBOURN A, KARESH W *et al.* - Wild animal mortality monitoring and human Ebola outbreaks, Gabon and Republic of Congo, 2001-2003. *Emerg Infect Dis*, 2005, **11**, 283-290.
21. SPECTER M - Nature's bioterrorist- Is there any way to prevent a deadly avian-flu pandemic? *The New Yorker*, 2005, February 28, 50-61.
22. TUCKER CJ, WILSON JM, MAHONEY R, ANYAMBA A, LINTHICUM KJ *et al.* - Climatic and Ecological Context of Ebola Outbreaks. Photogrammetric Engineering Remote Sensing. Special Issue on Remote Sensing and Human Health, **68**, 147-152.
23. WASHINO RK & WOOD BL - Application of remote sensing to arthropod vector surveillance and control. *Am J Trop Med Hyg*, 1994, **50**, 134-144.
24. WILSON JM & TUCKER CJ - Use of Remote Sensing in Epidemic Surveillance and Response. *World Meteorological Organ Bull*, 2002, **51**, 136-139.
25. WHO - Overview of the WHO framework for monitoring and evaluating surveillance and response systems for communicable diseases. *The Weekly Epidemiological Record*, 2004, **36**. http://www.who.int/mediacentre/factsheets/fs200/en/ http://www.who.int/csr/labepidemiology/projects/recommendations/en/